

### 19.4 Protection of Industrial Power Systems

The purpose of protection systems is to remove faulted and overloaded equipment promptly. They observe the following priorities:

- 1. Prevention of injuries to personnel.
- 2. Prevention of fires.
- 3. Prevention of damage to electrical equipment.
- 4. Minimization of disturbances to the unfaulted parts of the system.

Obviously, item 2 is closely related to items 1 & 3.

While protection systems are concerned with such things as overvoltages, phase-sequencing and undervoltages, we will mainly look at the effect of overcurrent conditions. These are mainly caused by *overloads* and *short-circuits*; the burdens that these events place on the system are quite different and require the protection system to respond differently.

**Overloads** result from excessive demand being placed on the system e.g. the mechanical load on a motor being increased until it draws current in excess of its rating; notice that it is not caused by equipment failure. Overloads can always be tolerated for a period of time, typically seconds or even minutes depending on the degree of overload and the capacity of the system. Removal of equipment is performed after an intentional delay has expired.

**Short-circuits** result from equipment failure, typically breakdown of insulation. The resulting fault currents can be very large, typically an order of magnitude above the rated current of the circuit. Removal of equipment is performed without any intentional delay; this is referred to as an *instantaneous trip* even though it may take a fraction of a second to complete the operation.

It's important that all protection devices be able to detect overload conditions and fault conditions and then respond accordingly. A basic requirement is that they should react very quickly to very large currents (faults) while reacting fairly slowly to minor overloads, and to not trip at all for currents below the rated value of the component they are protecting. This requirement is known as the *inverse-time* characteristic and a typical application is shown in figure 19.7, which is plotted on a log-log scale.

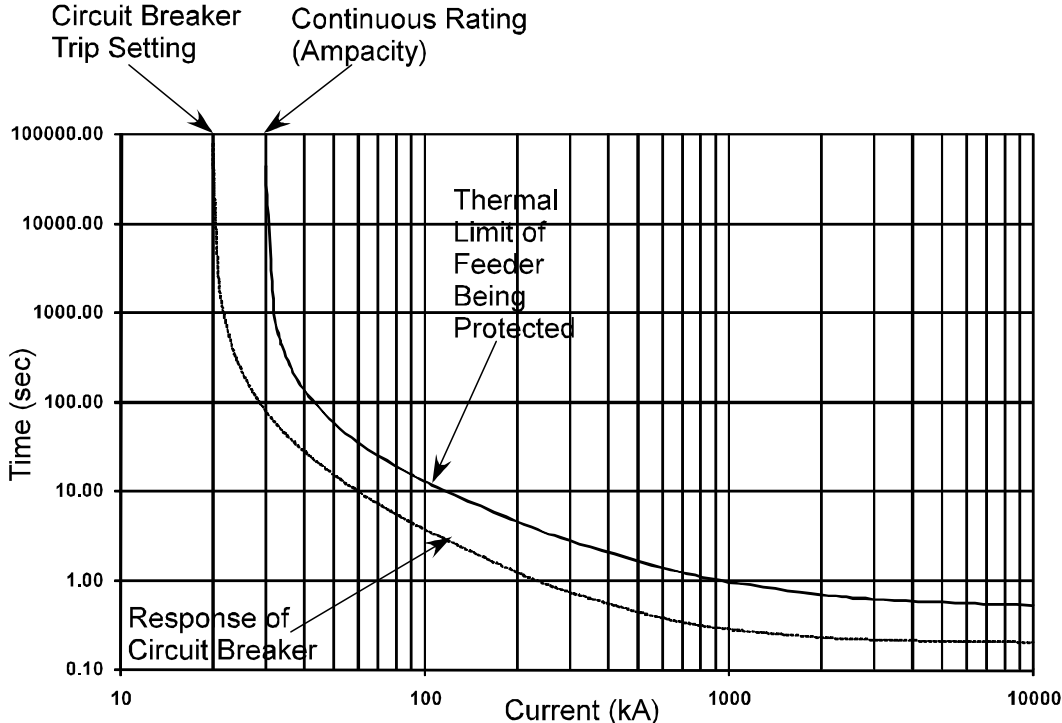


Figure 19.7 Inverse-Time Characteristic

The feeder shown in figure 19.7 has a rated current of 30 A, meaning that it can carry 30 A continuously without overheating. If it draws more than 30 A it will start to overheat, the time taken to damage the insulation depending on the amount that the 30 A rating is exceeded. Overloads are normally considered to be currents in the range 100% to 600% of the rating i.e. up to 180 A in figure 19.7. Currents above 600% are considered to be faults.

Figure 19.7 shows the ideal case in which the protection device always operates just before the feeder will sustain damage. In reality a larger margin will usually be required and the two lines will not bottom out at high currents as shown, they tend to nose-dive at very high currents.

The most common types of overcurrent protection devices are fuses and circuit breakers and these are described in the following sections.

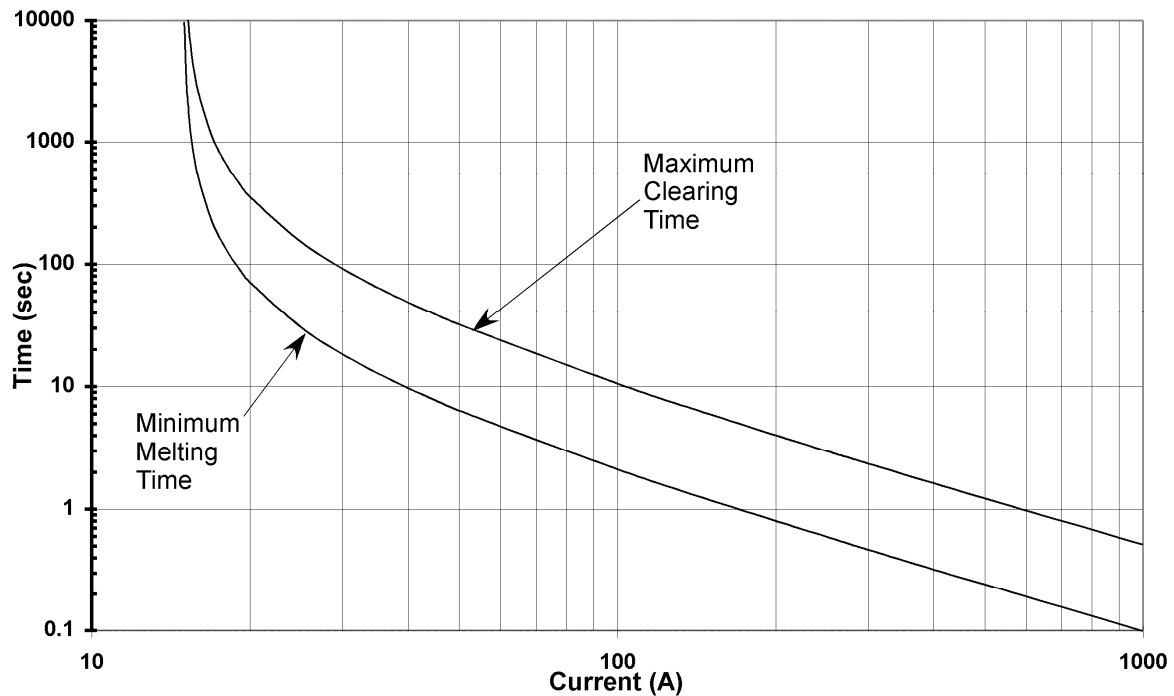
### 19.4.1 Fuses

Industrial fuses consist of a piece of conducting material called the *fusible element* that is enclosed in a cartridge-like assembly. The fuse carries the entire current that flows in the circuit being protected. This current heats the fusible element, which is naturally cooled. During overcurrent conditions the fuse link melts, emitting de-ionizing gasses that accumulate in the enclosure and prevent re-establishment of the arc after the current passes through zero. The length and cross-section of the fusible element determines the current vs. time relationship for melting of the element. Length determines the amount of heat that can be conducted away - a long element will reach melting temperature sooner than a short one during overcurrent (but not fault) conditions. Under fault conditions, the temperature rise is much faster and melting time depends on current magnitude and the cross-section of the fusible element.

A fuse will not instantly interrupt the circuit it is protecting when the current exceeds the rated value. The amount of heat going into the fusible element in a time period  $t$  seconds is  $W_{IN} = I^2Rt$ , where  $R$  is the resistance of the element. Conduction and convection will cool the element by an amount  $W_{OUT}$ . When  $W_{IN}$  exceeds  $W_{OUT}$  the element heats up and reaches its melting point. Obviously, the time taken to reach the melting point depends on the magnitude of the current.

After reaching its melting point the fuse will take additional time to interrupt the current as the fusible element melts and arcs. The general form of fuse melting and clearing is shown in figure 19.8; the characteristics are for a 15 A fuse. Note its similarity to the dotted line in figure 19.7, where instead of being a single line the fuse exhibits a range of times for a particular value of overload current.

## Fuse Characteristics



**Figure 19.8 Fuse Melting and Clearing Characteristics**

Fuses are divided into *low voltage* for applications up to 1 kV and *medium and high voltage* for applications over 1 kV.

The typical fusible element shown in figure 19.8 has excellent characteristics for overloads i.e. up to ~90 A (600% of rating) but would allow moderate faults to exist for several seconds before clearing them. For this reason a particular type of fuse called the *current-limiting fuse* was developed. It has an irregular shaped fusible element that melts extremely quickly when subjected to faults; it is also packed in a quartz filler that absorbs the heat from the arc and in so doing turns into a glass plug that prevents re-striking of the arc. The outcome is that the total clearing time is reduced to about 0.5 cycle (~8 ms) while the maximum current passing through the fuse is held to 50% of the peak value that would have occurred without the fuse.

In this sense, the current-limiting fuse provides instantaneous tripping under fault conditions.

The advantages and disadvantages of fuses as compared to circuit breakers can be summarized as follows:

**Advantages** are low cost, low maintenance, low space requirement, high current interrupting capacity, inherently fail-safe i.e. they open the circuit when they fail.

**Disadvantages** are no re-set capability (replacements required when they operate), can allow motors to run on two phases when only one fuse blows, not adjustable, can not switch loads on or off (must be used in combination with a switch to isolate the circuit.)

## 19.4.2 Circuit Breakers

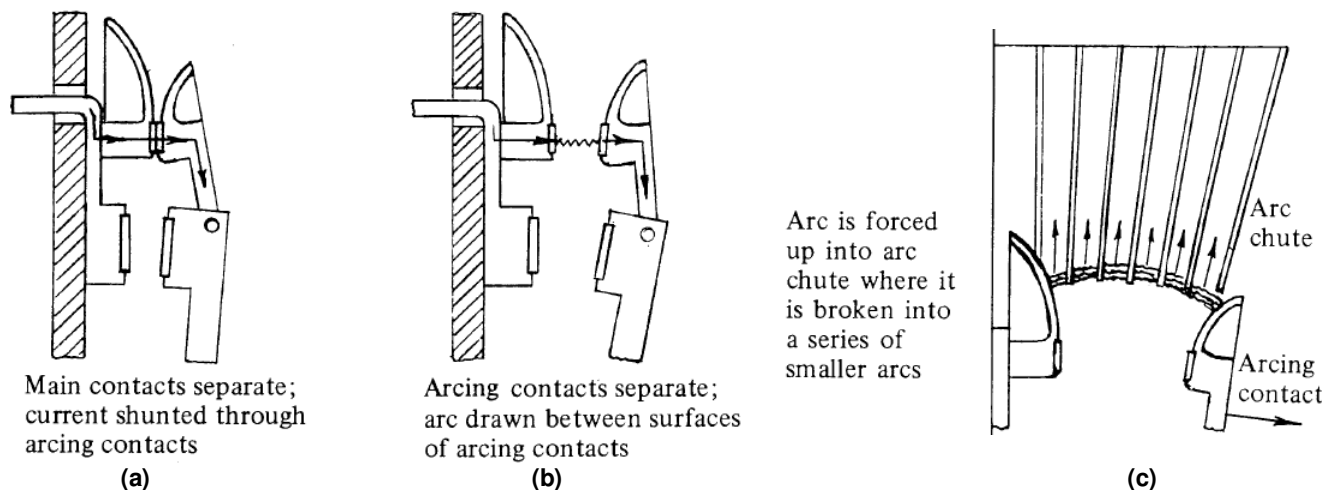
Circuit breakers interrupt current by opening two contacts, rather like a simple switch; however, if a simple switch were used in a power circuit the level of inductance (power circuits are highly inductive) causes an arc to be drawn across the open contacts. Remember that Lenz's Law tells us that the voltage induced across the open contacts is equal to inductance times the rate of change of current and since the arc consists of a stream of ionized particles any significant induced voltage will sustain the arc. This means that alternating currents can not be instantaneously interrupted. All circuit breakers have to deal with the problem of extinguishing the arc after the contacts have opened.

Like fuses, circuit breakers are divided into *low voltage* for applications up to 1 kV and *medium and high voltage* for applications over 1 kV. The mechanism of arc interruption is different for each voltage class. For the purpose of this chapter, we will only be concerned with low voltage (LV) Circuit Breakers

There are three basic types of LV circuit breakers: *molded-case breakers* are low cost and are used for low power applications, *power breakers* are more expensive and are used for relatively high power applications, while *enclosed-case* breakers blend the two preceding designs to take advantage of each.

Unlike their high voltage counterparts, LV breakers get their tripping power from the ac current they are monitoring. This is achieved by integrally mounted trip units that sense when tripping should occur. There are two trip units, one senses overload conditions and trips after an intentional time delay has elapsed in order to provide an opportunity for operators to relieve the overload without removing the equipment; the other senses the higher currents that correspond to fault conditions and trips with no intentional time delay.

The arc will damage the contacts and so *arcing contacts* are employed to prevent damage to the main contacts, which open before the arcing contacts as shown in figure 19.9a and 19.9b. Since the current can not be instantaneously interrupted, the arc will continue to flow until the arcing contacts have separated far enough to extinguish it following a natural current zero. This process is speeded up by the use of *arc chutes* that are parallel plates mounted near the contacts so that when the arc is drawn its magnetic field causes it to be stretched around the arcing chutes, as shown in figure 19.9c.



**Figure 19.9 Arc Interruption in Low-Voltage Circuit Breakers**

*Taken from Electric Systems in Buildings by S. David Hughes*

When specifying LV circuit breakers it is important to note that there are two values of current that need to be identified, these are:

- Frame size. This is the continuous current that the breaker can carry without overheating, it also determines the maximum current that the breaker can safely interrupt and the maximum continuous voltage.
- Trip level. This is the smallest value of current that will initiate tripping after the intentional time delay. This current is sometimes called *pickup*. For obvious reasons, it must always be less than or equal to the frame size.

A list of frame sizes for molded-case circuit breakers are presented in table 19.7, where Std stands for *Standard Duty* and HIC stands for *high interrupting capacity*.

Frame Size (A)	Rated Voltage (V)	Trip Range (A)	Maximum Interrupting Current (kA)		
			240 V	480 V	600 V
100 Std	240	15 - 100	10	-	-
100 HIC			65	-	-
100 Std	480	15 - 100	18	14	-
150 Std	600	15 - 150	18	14	14
150 HIC			65	25	18
225 Std	600	70 - 225	25	22	18
225 HIC			65	25	22
400 Std	600	125 - 400	42	30	22
400 HIC			65	35	25
600 Std	600	250 - 600	42	30	22
600 HIC			65	35	25
800 Std	600	400 - 800	42	30	22
800 HIC			65	50	25
1200 Std	600	600 - 1200	42	30	22
1200 HIC			65	50	25

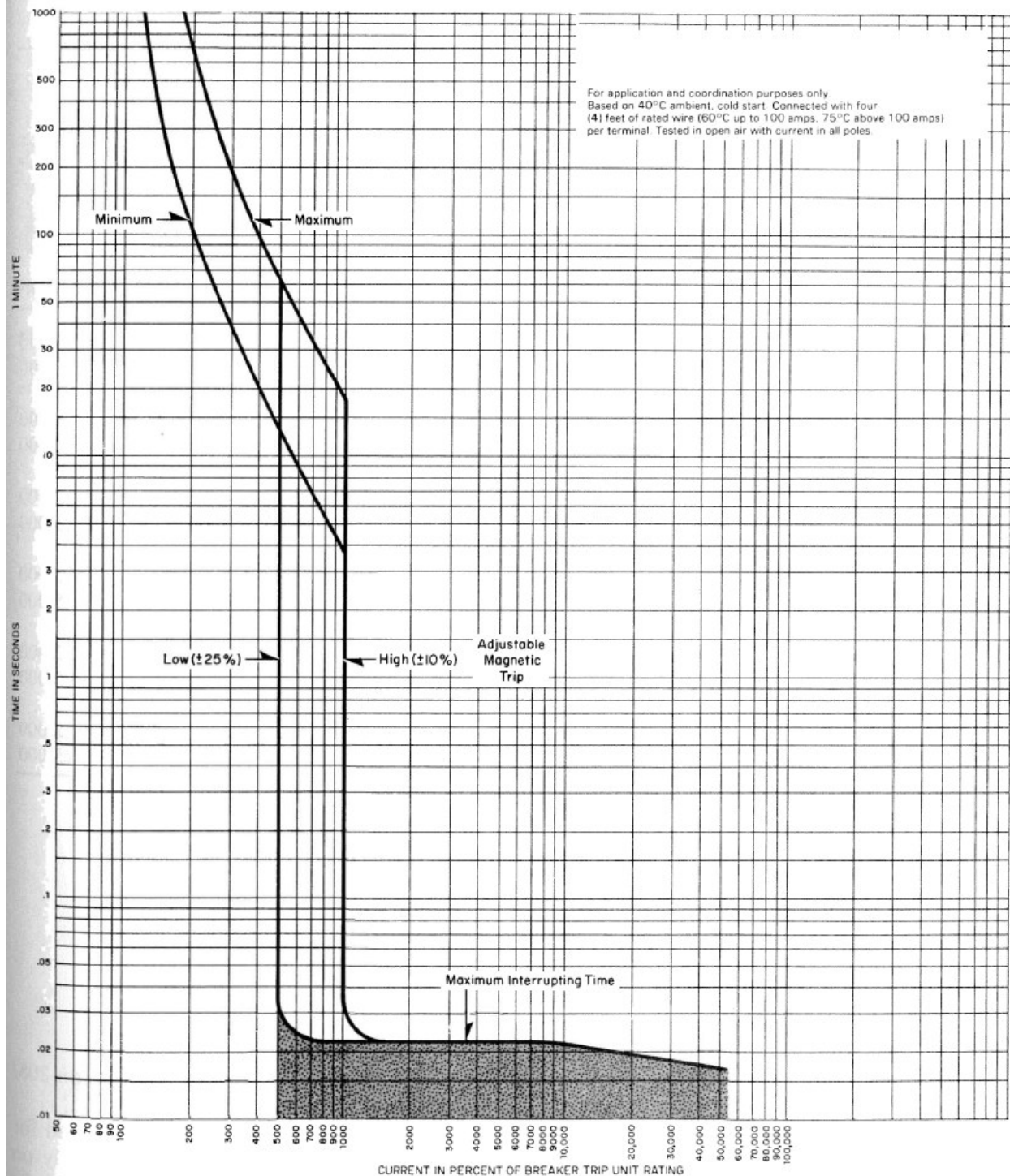
Standard trip ratings (A) are: 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600, 800, 1000, and 1200.

**Table 19.7 Frame Sizes and Maximum Interrupting Ratings for Molded Case Circuit Breakers**

*Taken from Electric Systems in Buildings by S. David Hughes*

Similar tables exist for other types of circuit breakers (power, enclosed-case and medium voltage).

A typical time vs. current characteristic of a molded-case circuit breaker is shown in figure 19.10. Note that the x-axis is not in amps but is in % of pickup current.



**Figure 19.10 Operating Time vs. Percent Pickup Current for 400 A Frame Size Molded Case Circuit Breaker**

*Taken from Electric Systems in Buildings by S. David Hughes*

The min and max lines on the inverse-time part of the graph are due to manufacturer's tolerances, while the low and high vertical lines represent an adjustable range for the instantaneous trip setting.

### EXAMPLE 19.7

For the breaker whose characteristics are shown in figure 19.10, with a 225 A pickup and the instantaneous trip set at 1800 A, determine the minimum and maximum tripping times for the following current levels.

- a) 200 A.
- b) 900 A.
- c) 2000 A

#### *Solution*

**Strategy:** The times can be read directly from the graph, but we need to identify if the currents are below pickup, above instantaneous, or in between pickup and instantaneous.

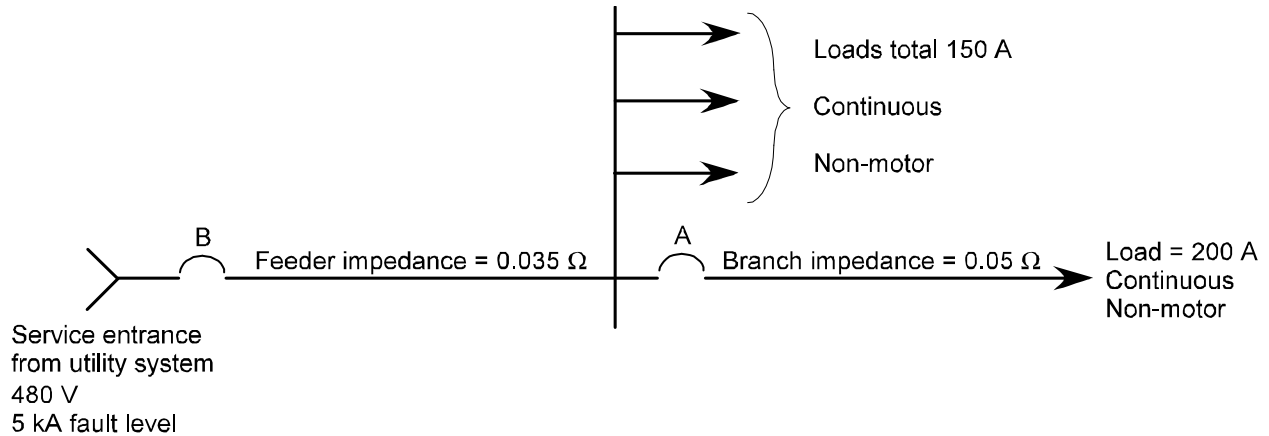
**Assumptions:** None.

**Analysis:**

When more than one circuit breaker is used to protect feeders, sub-feeders and branches, it is essential that they be *co-ordinated* i.e. the one nearest to the fault or overload should trip first, thus removing the minimum amount of equipment from service. This is demonstrated in the following example.

### EXAMPLE 19.8

The following diagram shows feeders and branches that are protected by molded-case breakers whose frame size is 400 A and are represented by the time vs. current graph of figure 19.10. Select suitable pickup and instantaneous trip settings for breakers A and B.



### Solution

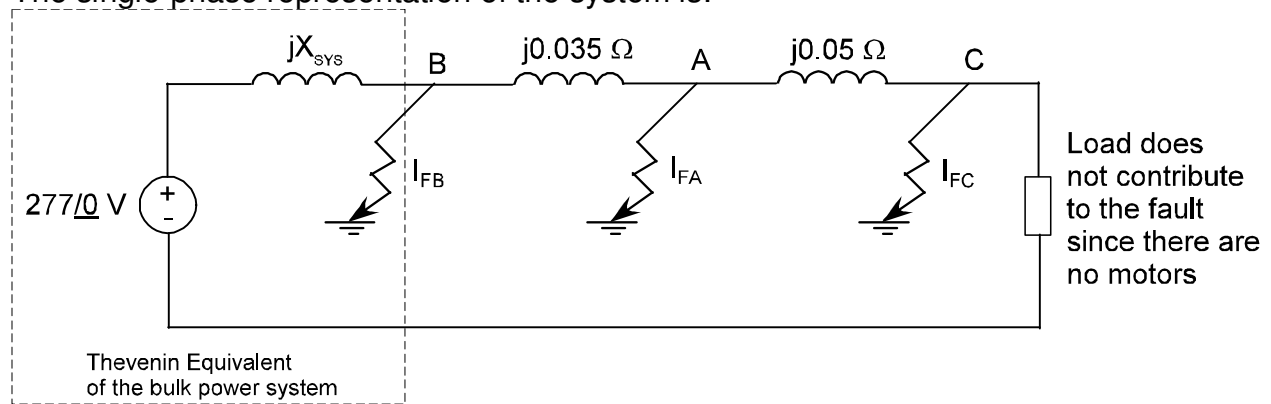
**Strategy:** Pickup levels should be greater than the expected load current, but less than the ampacity of the conductor, i.e. it should be within the 25% margin. The instantaneous trip levels should be set based upon the *smallest* fault current that the breaker will see, this is to ensure that *all* faults are cleared with the minimum of delay.

**Assumptions:** The bulk power system can be modeled using the techniques presented in chapter 18, example 18.8.

### Analysis:

To set the instantaneous trips we must determine the lowest fault levels at each breaker. We will employ the technique introduced in chapter 18 to do this (refer to example 18.8) except per-unit calculations are unnecessary since transformers are not involved.

The single-phase representation of the system is:



The advantages and disadvantages of circuit breakers as compared to fuses can be summarized as follows:

**Advantages** are ability to switch as well as protect a circuit, will not permit motors to run on two phases, will re-set after operation.

**Disadvantages** are significantly higher cost, larger hence requires more space, requires periodic maintenance, not inherently fail-safe i.e. can jam in the closed position.